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Estimating the contribution from different ionospheric regions to the TEC response to the solar flares using data from the international GPS network

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Abstract. This paper proposes a new method for estimating the contribution from different ionospheric regions to the response of total electron content variations to the solar flare, based on data from the international network of two-frequency multichannel receivers of the navigation GPS system. The method uses the effect of partial “shadowing” of the atmosphere by the terrestrial globe. The study of the solar flare influence on the atmosphere uses GPS stations located near the boundary of the shadow on the ground in the nightside hemisphere. The beams between the satellite-borne transmitter and the receiver on the ground for these stations pass partially through the atmosphere lying in the region of total shadow, and partially through the illuminated atmosphere. The analysis of the ionospheric effect of a powerful solar flare of class X5.7/3B that was recorded on 14 July 2000 (10:24 UT, N22 W07) in quiet geomagnetic conditions ($D_{st} = -10$ nT) has shown that about 75% of the TEC increase corresponds to the ionospheric region lying below 300 km and about 25% to regions lying above 300 km.

Key words. Ionosphere (solar radiation and cosmic ray effects; instruments and techniques) – Solar physics, astrophysics and astronomy (ultraviolet emissions)

1 Introduction

The enhancement of X-ray and ultraviolet (UV) emission that is observed during chromospheric flares on the Sun immediately causes an increase in electron density in the ionosphere. These density variations are different for different altitudes and are called Sudden Ionospheric Disturbances (SIDs) (Davies, 1990; Donnelly, 1969). SIDs are generally recorded as the short wave fadeout (SWF) (Stonehocker, 1970), sudden phase anomaly (SPA) (Ohshio, 1971), sudden frequency deviation (SFD) (Donnelly, 1971; Liu et al., 1996), sudden cosmic noise absorption (SCNA) (Deshpande and Mitra, 1972), and sudden enhancement/decrease of at-

mospherics (SES) (Sao et al., 1970). Much research is devoted to SID studies, among them a number of thorough reviews (Mitra, 1974; Davies, 1990).

A highly informative technique is the method of Incoherent Scatter (IS). The Millstone Hill IS facility recorded a powerful flare on 7 August 1972 (Mendillo and Evans, 1974a). The measurements were made in the height range from 125 to 1200 km. The increase in local electron density N_e made up 100% at 125 km altitude and 60% at 200 km.

Using the IS method, Thome and Wagner (1971) obtained important evidence of the height distribution of the increase in N_e at the time of the 21 and 23 May 1967 flares. A significant increase in N_e was recorded in the E-region, up to 200%, which gradually decreased in the F-region with increasing height, down to 10–30%, and remained distinguishable up to 300 km. The earliest increase in N_e began in the E-region, and at higher altitudes it was observed with a delay which is particularly pronounced at F-region heights.

A sudden increase in total electron content (TEC) can be measured using continuously operating radio beacons installed on geostationary satellites. On 7 August 1972, Mendillo et al. (1974b) were the first to make an attempt to carry out global observations of the solar flare using 17 stations in North America, Europe, and Africa. The observations covered an area, the boundaries of which were separated by 70° in latitude and by 10 h in local time. For different stations, the absolute value of the TEC increase ΔI varies from $1.8 \cdot 10^{16}$ to $8.6 \cdot 10^{16} \text{ el} \cdot \text{m}^{-2}$, which corresponds to 15–30% of the TEC. Investigations revealed a latitudinal dependence of the TEC increase value. At low latitudes, it was higher compared with high latitudes. Besides, the authors point out the absence of a connection between the TEC increase value and the solar zenith angle.

The advent and evolution of a Global Positioning System (GPS) and also the creation of widely branched networks of GPS stations (at least 900 sites by August 2001, the data from which are located on the Internet) opened up a new era in remote ionospheric sensing. High-precision measurements of the TEC along the line-of-sight (LOS) between the

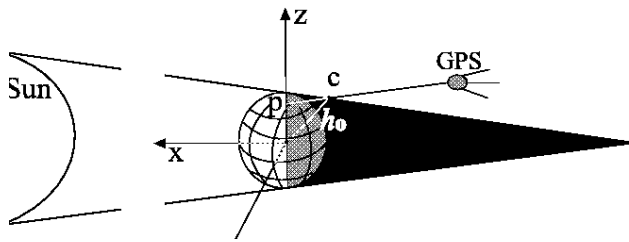


Fig. 1. Scheme for the determination of the shadow altitude h_0 over the ground in the GSE system. GPS – GPS navigation satellite; P – GPS station on the ground; C – intersection point of the transmitter – receiver LOS and the shadow boundary.

receiver on the ground and transmitters on the GPS system satellites covering the reception zone are made using two-frequency multichannel receivers of the GPS system at almost any point of the globe and at any time, simultaneously at two coherently coupled frequencies: $f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz.

The sensitivity of phase measurements in the GPS system is sufficient for detecting irregularities with an amplitude of up to $10^{-3} - 10^{-4}$ of the diurnal TEC variation. This makes it possible to formulate the problem of detecting ionospheric disturbances from different sources of artificial and natural origins. The TEC unit (TECU), which is equal to 10^{16} el \cdot m $^{-2}$ and is commonly accepted in the literature, will be used throughout the text.

Afraimovich (2000a) and Afraimovich et al. (2000b, 2001a, b) have developed a novel technology of a global detection of ionospheric effects from solar flares and presented data from first the GPS measurements of global response of the ionosphere to powerful impulsive flares of 29 July 1999 and 28 December 1999. The authors found that fluctuations of TEC are coherent for all stations on the dayside of the Earth. The time profile of TEC responses is similar to the time behavior of hard X-ray emission variations during flares in the energy range 25–35 keV if the relaxation time of electron density disturbances in the ionosphere of the order of 50–100 s is introduced. No such effect on the nightside of the Earth has been detected yet.

Afraimovich et al. (2001c, 2002) and Leonovich et al. (2001) have suggested a technique for estimating the ionospheric response to weak solar flares (of X-ray class C). They obtained a dependence of the ionospheric TEC increase amplitude (during the solar flare) on the flare location on the Sun (on the central meridian distance, CMD). For flares lying closer to the disk center ($\text{CMD} < 40^\circ$), an empirical dependence of the ionospheric TEC increase amplitude on the peak power of solar flares in the X-ray range was obtained (using data from the geostationary GOES-10 satellite).

This paper is a logical continuation of the series of our publications (Afraimovich, 2000a; Afraimovich et al., 2000b, 2001a, b, c, 2002; Leonovich et al., 2001) devoted to the study of ionospheric effects of solar flares, based on data from the international GPS network.

A limitation of the GPS method is that its results have an integral character. It is therefore impossible to determine (from measurement at a single site) the particular ionospheric region which makes the main contribution to the TEC variation. The objective of this study is to develop a method which would help overcome (at least partially) this problem.

2 Method of determining the shadow altitude h_0 over the ground

The method uses the effect of partial “shadowing” of the atmosphere by the terrestrial globe. Direct beams of solar ionizing radiation from the flare do not penetrate the region of the Earth’s total shadow. GPS stations located near the shadow boundary on the ground in the nightside hemisphere are used to investigate the solar flare influence on the ionosphere. The LOS for these stations pass partially through the atmosphere lying in the total shadow region, and partially through the illuminated atmosphere. The altitude over the ground at which the LOS intersects the boundary of the total shadow cone will be referred to as the shadow altitude h_0 .

Figure 1 schematically represents the formation of the cone of the Earth’s total shadow (not to scale) in the geocentric solar-ecliptic coordinate system (GSE): the axis Z is directed to a north perpendicular planes of an ecliptic, and the axis X – on the Sun, and the axis Y is directed perpendicular to these axes. For a definition of the shadow altitude h_0 , it is necessary to know the coordinates of a cross point C of the LOS and the shadow boundary.

The primary data are the geographical coordinates of station GPS on the Earth (Fig. 1; a point P): an elevation angle θ and azimuth of LOS on a satellite GPS, toward the north clockwise, for the time (UT), corresponding to the phase of solar flare maximum in the X-ray range. These coordinates are converted to the Cartesian coordinate system, where the Cartesian coordinates of the GPS station on the ground and the coordinates of the subionospheric point (at 300 km altitude) are calculated. Next, we use the geocentric solar-ecliptic coordinate system following the technique reported by Sergeev and Tsyganenko (1980). To determine the coordinates of the point C, we solve a system of equations: the equation of a cone (of total shadow), and the equation of a straight line (LOS) specified parametrically. After that, from the resulting point C, we drop a perpendicular to the ground and calculate its length (Fig. 1, line h_0). Thus, the obtained value of h_0 is just the shadow altitude.

3 Method of determining the TEC increase in the ionosphere using data from the global GPS network

This paper exemplifies an analysis of the ionospheric effect of a powerful solar flare of class X5.7/3B recorded on 14 July 2000 (10:24 UT, N 22 W 07) under quiet geomagnetic conditions ($D_{st} = -10$ nT). The time profile of soft X-ray emission in the range 1–8 Å (GOES-10 data) at the time of the flare is presented in Fig. 2a.

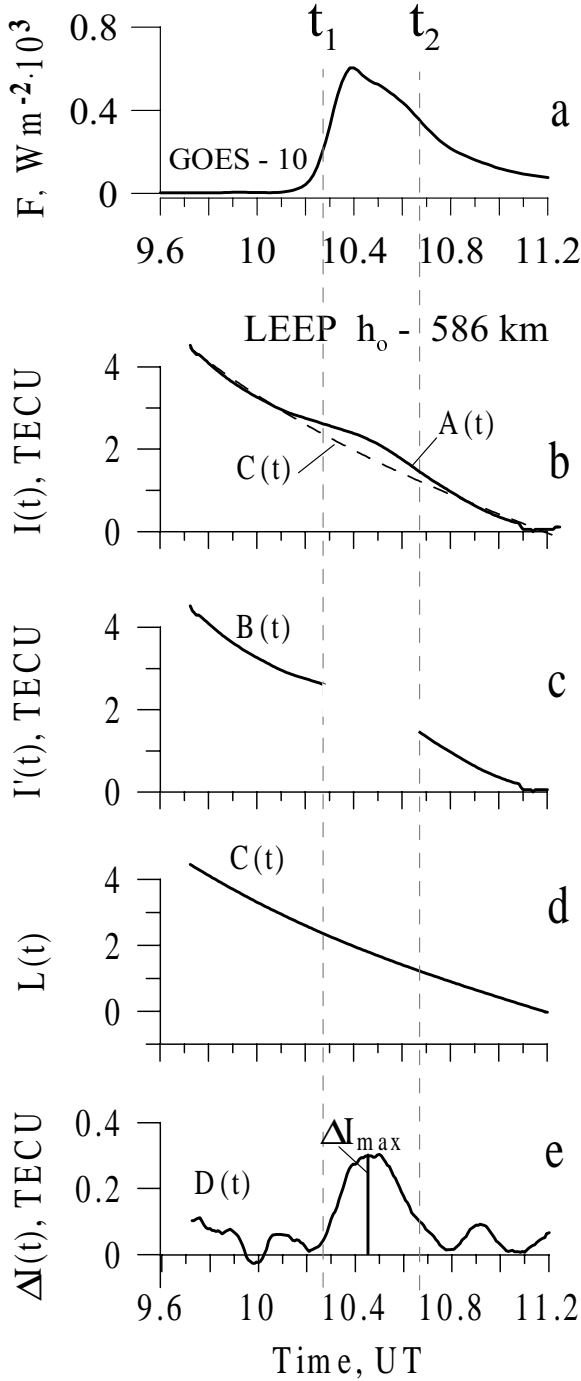


Fig. 2. Time profile of soft X-ray emission in the range 1–8 Å (GOES-10 data) during the solar flare of 14 July 2000 (a). Time dependence of TEC variations for the station LEEP A(t) (PRN07, shadow height $h_0 = 586$ km) (b), solid line. The same dependence after removal of counts in interval $(t_1 - t_2)$ (c) is represented by curve B(t). (d) is the curve C(t) (third-degree polynomial) approximating the time dependence B(t). This same curve is plotted in panel (b) by a dashed line. Time dependence of TEC variations D(t) upon subtracting the polynomial (e).

To determine the TEC increase in the ionosphere we used the data from the international GPS network. The GPS tech-

nology provides a means of estimating the TEC variations $I_0(t)$ on the basis of TEC phase measurements made with each of the spatially separated two-frequency GPS receivers using the formula (Calais and Minster, 1996):

$$I_0(t) = \frac{1}{40.308} \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} [(L_1 \lambda_1 - L_2 \lambda_2) + \text{const} + nL], \quad (1)$$

where $L_1 \lambda_1$ and $L_2 \lambda_2$ are the increments of the radio signal phase path caused by the phase delay in the ionosphere (m); L_1 and L_2 stand for the number of complete phase rotations, and λ_1 and λ_2 are the wavelengths (m) for the frequencies f_1 and f_2 , respectively; const is some unknown initial phase path (m); and nL is the error in determining the phase path (m).

Input data used in the analysis include a series of the “oblique” values of TEC $I_0(t)$, as well as a corresponding series of elevations θ and azimuths of LOS to the satellite. These parameters are calculated using our developed CONVTEC program to convert standard (for the GPS system) RINEX-files received via the Internet. Input series of TEC $I_0(t)$ are converted to the “vertical” value following a well-known technique (Klobuchar, 1986):

$$I(t) = I_0 \cdot \cos \left[\arcsin \left(\frac{R_E}{R_E + h_{\max}} \cos \theta \right) \right], \quad (2)$$

where R_E is Earth’s radius; and h_{\max} is the height of the ionospheric F2-layer maximum.

Variations of the regular ionosphere, as well as trends introduced by the motion of the satellite, are eliminated using the procedure of removing the trend. The procedure of eliminating the trend for each realization is presented in Fig. 2. The time profile of soft X-ray emission in the range 1–8 Å (GOES-10 data) during the solar flare of 14 July 2000 is shown in Fig. 2a. Figure 2b (solid line) presents the typical time dependence of vertical TEC A(t) for the site GPS LEEP (PRN07, shadow height $h_0 = 586$ km). From this dependence we eliminated the counts corresponding to interval $(t_1 - t_2)$, during which (according to GOES-10 data) soft X-ray emission showed the phase of flare maximum (from 10:18 to 10:35 UT) – Fig. 2b, curve B(t). The dependence B(t), obtained by this procedure, was approximated by a third-order polynomial C(t) using the least-squares technique. The polynomial C(t) is shown in Figs. 2d and c by a dashed line. The resulting TEC response D(t) is deduced as a difference: $D(t) = A(t) - C(t)$, Fig. 2e. A maximum value of the response ΔI_{\max} , shown in Fig. 2e by a vertical line, is then used to estimate the contribution from different ionospheric regions to the TEC response.

4 Results and discussion

The TEC response to the solar flare was analyzed for 45 GPS stations. Detailed information about the GPS stations and analysis results is summarized in Table 1: names of GPS receiving stations (Site), number of the GPS satellites from

Table 1. Parameters of response TEC during solar flare of 14 July 2000

Site GPS	PRN	h_0 km	ΔI_{\max} TECU	M %	latitude degree	longitude degree
STB1	2	0	1.1	100	44.7	272
KAYT	21	0	1.06	96.3	13.9	120
STL4	2	15	1.1	100	38.6	270
WDLM	2	16	1.07	97.2	44.6	264
SLAI	2	21	1.09	99.0	41.9	266
GUS2	2	65	1.0	90	58.3	225
PRDS	9	80	1.1	100	50.8	245
CORD	1	92	1.0	90.9	-31.5	295
WILL	2	107	0.9	81.8	52.2	237
YAR1	17	112	1.0	90.9	-29.0	115
PLTC	2	140	0.83	75.4	40.1	255
VCIO	7	141	0.8	72.7	36.0	260
TMGO	2	147	0.72	65.4	40.1	254
PATT	7	147	0.71	64.5	31.7	264
DSRC	2	150	0.7	63.6	39.9	254
LKWY	9	152	0.71	64.5	44.5	249
PERT	30	155	0.66	60	-31.8	115
NANO	2	175	0.54	49.0	49.2	235
WHD1	2	185	0.5	45.4	48.3	237
SEAW	2	194	0.41	37.2	47.6	237
UCLU	2	195	0.5	45.4	48.9	234
SEAT	2	195	0.49	44.5	47.6	237
LIND	9	205	0.46	41.8	47	239
SEAW	9	206	0.42	38.1	47.6	237
GOBS	2	221	0.44	40	45.8	239
SATS	2	222	0.34	30.9	46.9	236
GWEN	2	227	0.32	29.0	45.7	238
LMUT	2	233	0.4	36.3	40.2	248
LKHU	4	234	0.39	35.4	29.9	264
AZCN	7	280	0.35	31.8	36.8	252
FTS1	7	280	0.3	27.2	46.2	236
SHIN	2	339	0.29	26.3	40.5	239
TUNG	9	344	0.28	25.4	40	241
SMYC	9	412	0.3	27.2	36.3	244
JAB1	17	413	0.3	27.2	-12.6	132
UCLP	2	483	0.31	28.1	34.0	241
CVHS	9	520	0.27	24.5	34.0	242
LEEP	7	585	0.28	25.4	34.1	241
PMHS	7	590	0.25	22.7	33.9	241
UCLP	7	590	0.26	23.6	34.0	241
CSDH	7	594	0.25	22.7	33.8	241
YBHB	26	685	0.24	21.8	41.7	237
RIOG	13	704	0.25	22.7	-53.7	292
PTSG	26	719	0.26	23.6	41.7	235
GUAM	26	885	0.23	20.9	15.5	154

which the signal is received (PRN), shadow altitude above the ground (h_0), absolute increase in TEC ΔI_{\max} , relative increase of TEC $M = \Delta I_{\max} / \Delta I_0$, and geographical coordinates of GPS stations (latitude, longitude). The increase of TEC ΔI_0 corresponds to the amplitude of the TEC increase measured at the station lying at the shadow boundary on the ground ($h_0 = 0$).

Figure 3b illustrates examples of time dependencies of the TEC $\Delta I(t)$ response for LOS to the satellites which intersect the boundary of the shadow cone at different heights h_0 during the solar flare of 14 July 2000. Figure 3b (left) presents the values of these altitudes, and (right) the names of the corresponding stations. For a better visualization, the

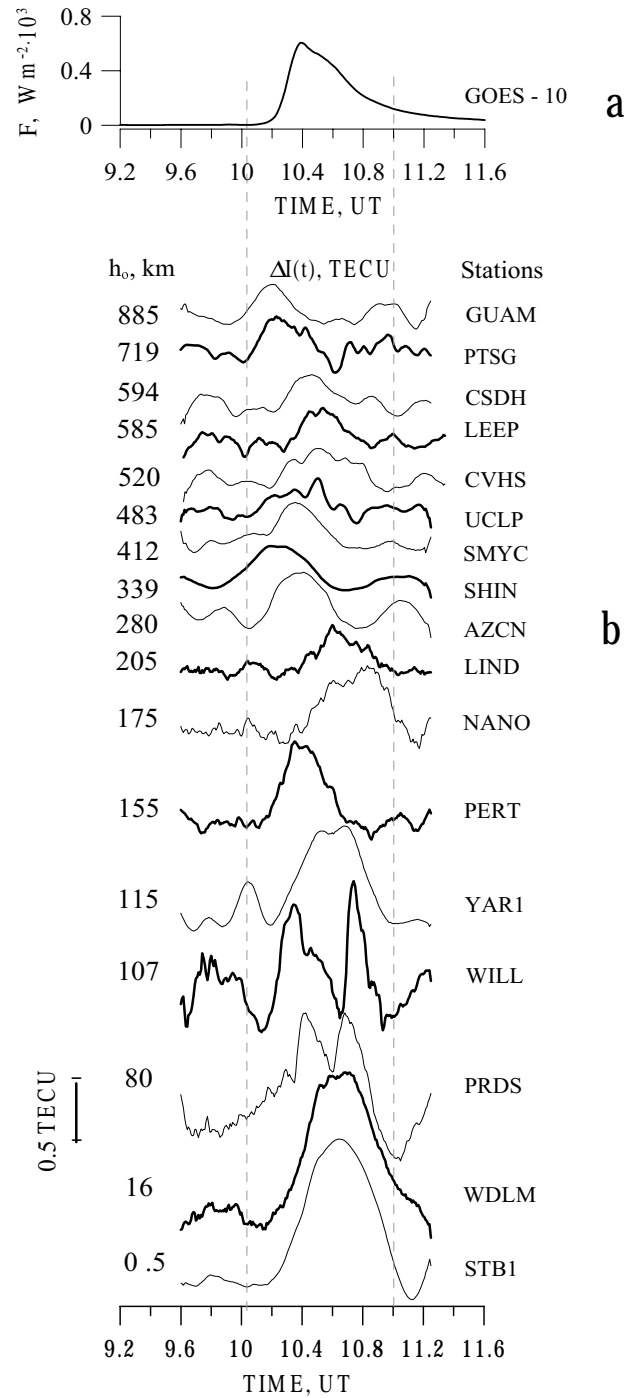


Fig. 3. Time profile of soft X-ray emission in the range 1–8 Å (GOES 10 data) (a). Examples of time dependencies of the TEC response $\Delta I(t)$ for LOS intersecting the boundary of the shadow cone at different altitudes h_0 during the solar flare of 14 July 2000 (for a better visualization, the dependencies are drawn by lines of different thicknesses); the column at the left shows the values of these heights, and the column at the right shows the names of the corresponding stations (b).

dependencies are drawn by lines of a different thickness. It should be noted that the response remains pronounced when

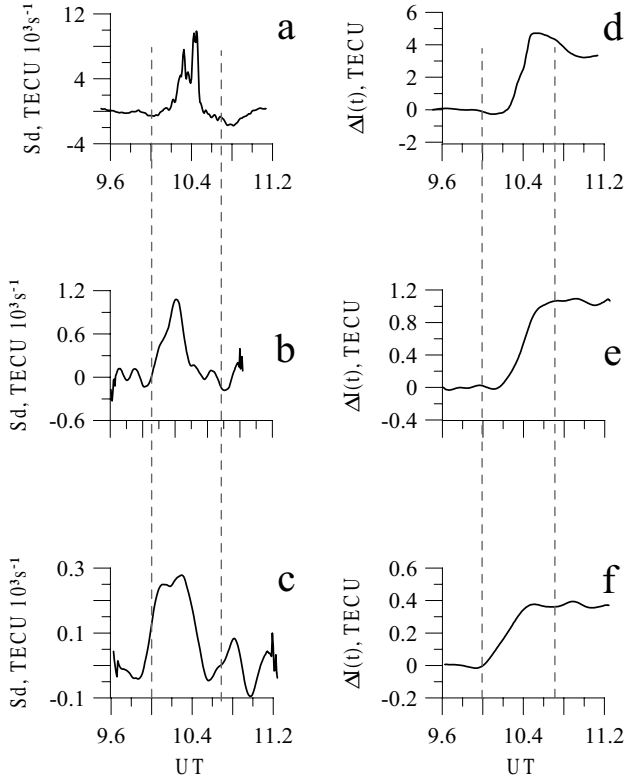


Fig. 4. Comparison of the TEC response for different conditions of atmospheric illumination. The result of a coherent accumulation of the TEC time derivatives Sd_{ex} (a), and the mean integral TEC increment $\Delta I(t)$ (d) for stations located in the Earth's illuminated hemisphere. Similar results for stations lying along the terminator line (b), (e), and for LOS crossing the shadow boundary at altitudes higher above 300 km (c), (f). Dashed lines correspond to the start and end times of the soft X-ray flare (GOES-10, 1–8 Å).

the shadow altitude exceeds significantly the electron density peak height in the ionosphere. For station GUAM (PRN26, height of the shadow boundary $h_0 = 885$ km), the response amplitude exceeds the background oscillation amplitude by more than a factor of 2.

It is evident from Fig. 3 that the wave phase (time of the response maximum) is different at different altitudes h_0 . On the one hand, this phenomenon can be caused by the interference of the response with background fluctuations; on the other, this can be due to the fact that at different heights different wavelengths of ionizing radiation are observed, which, in turn, can have independent time characteristics.

By virtue of the fact that the response amplitude at high altitudes was found to be comparable with the level of background fluctuations, the method of coherent accumulation by Afraimovich (2000a) and Afraimovich et al. (2000b, 2001a, b, c) was used in an additional analysis. The essence of the method is that it involves a coherent summation of TEC responses to the solar flare, which are measured simultaneously with all LOS chosen for the analysis. The analysis used spatially distributed stations to provide a statistical in-

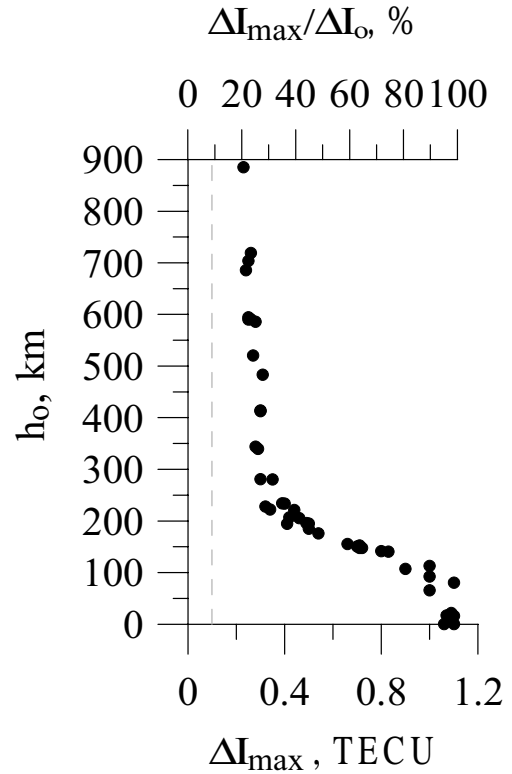


Fig. 5. Dependence of the absolute TEC increase ΔI_{\max} on the shadow altitude h_0 during the solar flare of 14 July 2000. The dashed line on the plot corresponds to the root-mean-square deviation of background oscillations in the absence of a flare. The upper scale shows the dependence of the relative TEC increase $\Delta I_{\max}/\Delta I_0$ on the shadow altitude h_0 during the solar flare in percent. The TEC increase ΔI_0 corresponds to the amplitude of the TEC increase measured at the station lying on the shadow boundary on the ground $h_0 = 0$.

dependence of background fluctuations for spaced LOS. Assuming that the TEC response to the solar flare is the signal and the background TEC fluctuations are noise, it is found that because the background fluctuations are not correlated at spaced LOS, the signal-to-noise ratio increases through a coherent processing no less than by a factor of \sqrt{N} , where N is the number of the LOS used.

In the present case, the coherent summation of the time derivatives was used for all dependencies of the “vertical” TEC value under investigation. The time derivative was used because it permits us to do away with the constant component in TEC variations; furthermore, it reflects the rate of electron density variation proportional to the flux of ionizing radiation. After that, the trend was removed from the averaged sum of the time derivatives using the procedure outlined above. This was followed by an integration of the calculated time dependence, Sd_{ex} , to give the mean integral TEC increment on a given time interval.

The method of coherent accumulation was employed to carry out a comparative analysis of the TEC response for different conditions of atmospheric illumination. Figure 4

presents the averaged results on a coherent accumulation of the TEC time derivatives, Sd_{ex} , and the corresponding integral TEC increments $\Delta I(t)$ for stations located in the Earth's illuminated hemisphere (a, d), for stations lying along the terminator line (b, c), and for LOS crossing the shadow boundary at altitudes above 300 km (c, f). For the conditions of full illumination, the terminator conditions and shadowing conditions, averaging was done over 50, 15 and 16 LOS, respectively.

The analysis reveals that the mean amplitude of the TEC response in the daytime hemisphere is larger by a factor of 4 than the response along the terminator line. In spite of the fact that the mean response amplitude along the LOS crossing the shadow boundary at altitudes above 300 km is nearly smaller by a factor of 3 than that along the terminator line, the response was sufficiently well pronounced. The coherent accumulation result confirms the presence of the response at altitudes above 300 km.

The dependence of the absolute TEC increase (ΔI_{\max}) on the altitude h_0 for all the cases under consideration is plotted in Fig. 5. The upper scale shows the dependence of the relative TEC increase $M = \Delta I_{\max} / \Delta I_0$ on the shadow altitude h_0 during the solar flare in percent. The TEC increase ΔI_0 corresponds to the amplitude of the TEC increase measured at the station lying on the shadow boundary on the ground $h_0 = 0$.

Figure 5 suggests that about 75% of the TEC increase corresponds to the ionospheric region lying below 300 km and about 25% to regions lying above 300 km. We found that a rather significant contribution to the TEC increase is made by ionospheric regions lying above 300 km.

The estimate obtained is consistent with the findings reported by Mendillo and Evans (1974a); Mendillo et al. (1974b). The authors of the cited references, based on investigating the electron density profile in the height range from 125 km to 1200 km using the IS method, concluded that about 40% of the TEC increase during the powerful flare on 7 August 1972 corresponds to ionospheric regions lying above 300 km. However, Thome and Wagner (1971), who used the IS method to investigate the ionospheric effects from two others powerful solar flares, pointed out that an increase in electron density associated with the solar flare was observable to 300 km altitude only. This difference can be explained by the fact that each particular solar flare is a unique event which is characterized by its own spectrum and dynamics in the flare process.

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